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Functional Categories for Future Flight Deck Designs

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Abstract

With the addition of each new system on the flight deck, the danger of increasing overall operator workload while reducing crew understanding of critical mission information exists. The introduction of more powerful onboard computers, larger databases, and the increased use of electronic display media may lead to a situation of flight deck "sophistication" at the expense of losses in flight crew capabilities and situational awareness. To counter this potentially negative impact of new technology, research activities are underway to re-assess the flight deck design process. The fundamental premise of these activities is that a human-centered, systems-oriented approach to the development of advanced civil aircraft flight decks will be required for future designs to remain ergonomically sound and economically competitive.

One of the initial steps in an integrated flight deck process is to define the primary flight deck functions needed to support the mission goals of the vehicle. This would allow the design team to evaluate candidate concepts in relation to their effectiveness in meeting the functional requirements. This could then allow for a better understanding and allocation of activities in the design, an understanding of the impact of a specific system on overall system performance, and an awareness of the total crew performance requirements for the design. This paper describes one candidate set of functional categories that could be used to guide an advanced flight deck design.

Introduction

Traditionally, the design of civil aircraft flight decks is an evolutionary, technology-driven process. By employing this approach, only incremental changes are required from the previous design to correct problems and add new systems. Additionally, changes to the current design may directly benefit from problems observed in the use of the previous design. This evolutionary approach is relatively low-risk and affords the design team a bottom-up set of requirements that are reasonably straightforward to implement. It is technology-centered in that new technologies are often introduced for economic reasons or if they can out-perform the flight crew on a particular task or function.

It should be noted, however, that each introduction of new technology into the flight deck has the potential to change the role of the flight crew. These changes have usually

occurred through the evolutionary addition of systems on the flight deck, not through a deliberate effort in the design. While the design and integration of any specific system into the flight deck may be perceived as a benefit to the crew, the actual synergistic effect may be the opposite. Moreover, the design of any new system may be quite good when considered as an individual system, but may not be as good when considered as part of the overall cockpit system. In some instances, the role of the crew has changed from a systems manager to a systems monitor or to a data "pipe" between systems. Either of these circumstances may result in a series of cognitively disjointed tasks for the flight crew and eventually lead to a loss of overall situational understanding and a reduction of crew performance.

With the addition of each new system on the flight deck, the danger of increasing overall operator workload while reducing crew understanding of critical mission information

exists. The introduction of more powerful onboard computers, larger databases, and the increased use of electronic display media may lead to a situation of flight deck "sophistication" at the expense of losses in flight crew capabilities and situational awareness. To counter this potentially negative impact of new technology, both industry and government research activities are underway to re-assess the flight deck design process.

The fundamental premise of these activities is that a human-centered, systems-oriented approach to the development of advanced civil aircraft flight decks will be required for future designs to remain ergonomically sound and economically competitive. One of the tenets of this approach is that overall functional requirements, at a flight deck level and based on aircraft mission goals, must be defined and expanded prior to defining and developing systems to support the overall requirements. In this regard, this design approach is not technology-driven but is mission-requirements driven where flight deck design, an automation-use philosophy, and the role of the flight crew are based directly on supporting the mission functional requirements. It is assumed that by using this design approach, many of the systems integration "problems" observed on today's flight decks could be greatly reduced, since definition and integration occur at the flight deck design level, not at the subsystem component level. Obviously, this design approach would provide the greatest contribution in a situation where a totally new flight deck design is possible.

A second tenet of this approach is the concept of human-centered design (ref. 1). To assure maximum performance of the combined flight-crew flight-deck system, the allocation of functions and the design of systems should be human-centered. In this context, human-centered is used to describe a philosophy in which the role of the flight crew is defined and the automation is then designed to support it. Human-centered design means that automation

and system implementation will not inadvertently change the role of the flight crew; rather, the role of the flight crew will shape the automation.

One of the initial steps in developing a requirements-driven, integrated flight deck design process is to define the primary flight deck functions needed to support the mission goals of the vehicle (refs. 2 to 4). This would allow the design team to evaluate candidate concepts in relation to their effectiveness in meeting the functional requirements. If the functional requirements also describe the functional priorities relative to the operational role of the flight crew, then this approach will allow for the early analysis (in the design cycle) of the impact of specific design decisions on the crew. That is, a framework would be available to aid in categorizing and bookkeeping all of the activities that are required to be performed on the flight deck, not just activities of the crew or of a specific system. This could then allow for a better understanding and allocation of activities in the design, an understanding of the impact of a specific system on overall system performance, and an awareness of the total crew performance requirements for the design. This paper describes one candidate set of functional categories that could be used to guide an advanced flight deck design.

The author would like to note that the concepts developed in this paper are a product of the Cockpit Integration Technology activity at the Langley Research Center. This activity was initiated to develop and demonstrate a systems engineering approach to the design of advanced civil aircraft flight decks.

Nomenclature

Abbreviations

FAR:	Federal Aviation Regulation.
MCP:	Mode control panel

Definitions

corrective state:	the intermediate state required to transition from a current state to a desired state.
current state:	the existing state.
desired state:	the state that would satisfy a goal or subgoal.
function:	a description of what needs to be done to satisfy a goal. A differentiable means whereby the system requirements are met (ref. 5).
goal:	the desired objective or result.
plan:	a scheme or procedure to accomplish an activity.
state:	the condition, mode, status, or situation.
subfunction:	a function that fulfills part of the requirements of a higher level function.
subgoal:	a goal that fulfills part of the requirements of a higher level goal.
subplan:	a plan that fulfills part of the requirements of a higher level plan.

Systems-Oriented Design

Systems-oriented design is the use of systems engineering (refs. 5 and 6) and systems thinking (ref. 7) to provide a structured approach for the design and construction of large, complex systems. An initial part of this design approach is function analysis, where functions generally describe what actions are needed to be accomplished to satisfied the

system objectives. Function analysis is the process of decomposing the design objectives of the system into a set of functions required to met the goals of these objectives. That is, broad, general functions are broken into subfunctions where these subfunctions are more constrained and more defined than the higher-level function from which they were produced. It is noteworthy that a subfunction at one level is a function at another. An example of this is shown in figure 1.

Major Categories

In defining the functional categories, the following two assumptions were made. First, the mission goal of the vehicle was to move passengers and cargo from airport gate to airport gate safely and efficiently. The second assumption was that the overall function of the flight deck (overall system objective) was to manage the mission of the vehicle. In addition, the overall flight deck function would include considerations for both normal and abnormal situations in the accomplishment of the vehicle mission. To support this overall function, four first-level functions or categories were defined: flight management, communications management, systems management, and task management. In some respects, these four first-level functions may seem to be a rendition of the traditional piloting functions of "aviate, navigate, and communicate." (The traditional "aviate, navigate, and communicate" define not only the primary piloting functions, but also the priority of these functions.) However, these functions are defined from a total flight deck system perspective instead of only from a pilot perspective. The definitions of these four first-level functions are given in the following sections and the reader will see how they differ from these traditional categories. The four first-level functions and their subfunction structure are shown in table 1.

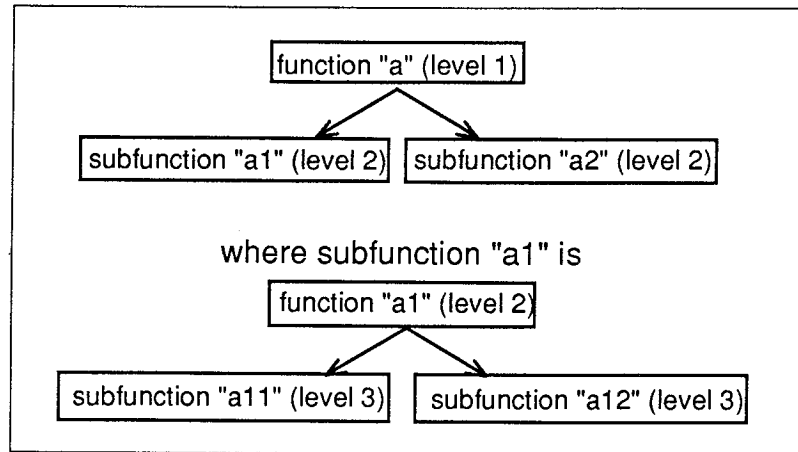


Figure 1. Example of function and subfunction relationships.

Table 1. First-level functions and their subfunction structure.

Flight management	Communications management	Systems management	Task management
<ul style="list-style-type: none"> • Flight guidance <ul style="list-style-type: none"> - Planning - Monitoring - Assessing - Determining actions - Modifying • Flight control <ul style="list-style-type: none"> - Planning - Monitoring - Assessing - Determining actions - Modifying 	<ul style="list-style-type: none"> • Receiving <ul style="list-style-type: none"> - Monitoring - Acquiring - Storing • Processing <ul style="list-style-type: none"> - Interpreting - Evaluating - Formulating • Sending 	<ul style="list-style-type: none"> • Configuration planning • Monitoring • Assessing <ul style="list-style-type: none"> - Comparing - Diagnosing • Determining actions • Modifying 	<ul style="list-style-type: none"> • Monitoring • Scheduling • Allocating
where: <ul style="list-style-type: none"> • second-level function - third-level function 			

Flight Management

Flight management is the first-level function of managing all parameters relative to flight planning, guidance, and control. This function directly supports the mission goal of the vehicle (to move passengers and cargo from airport gate to airport gate safely and efficiently). This function is more comprehensive than the functionality of a conventional flight management system and is more analogous to the "what" that the dispatcher and the flight deck crew must perform relative to flight planning,

guidance, and control. The flight management function itself was divided into two major subfunctions: flight guidance and flight control. These two subfunctions themselves were further subdivided as shown in figure 2.

Under this flight management function, two major subfunctions were developed: flight guidance and flight control. For these definitions, the flight guidance subfunction is considered to be the strategic part of flight management and the flight control subfunction is

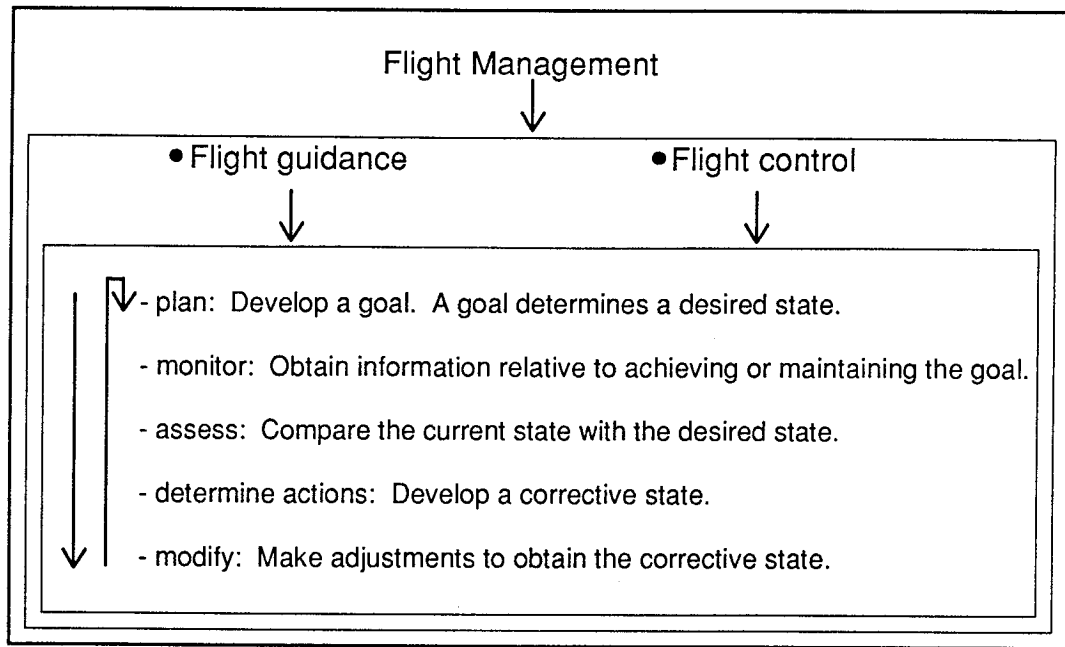


Figure 2. Subfunctions of flight management.

the tactical part. These subfunctions are further expanded as follows:

Flight guidance: Flight guidance is the function of developing a desired plan of flight, determining necessary resources, assessing the current situation, monitoring the progress of the flight, and adjusting the plan of flight as necessary. In this definition, it is important to note that the plan of flight is much more encompassing than what is traditionally considered a "flight plan." Flight guidance may be further divided into the following elements (third level subfunctions).

Planning: This element involves the determination of the destination airport and other intermediate goals to include: flight-environmental factors, FARs and other pertinent regulations, flight-planning procedures, and the resources necessary to obtain those goals. The planning goals include the determination of lateral, vertical, and speed (or speed and time) routing subgoals. An example of part of this activity would be defining the desired lateral profile to fly from Denver to Seattle.

Monitoring: This element involves the gathering of all available information about the current vehicle state and the desired vehicle state. That is; where am I, where am I supposed to be? This includes the gathering of information relative to the current environmental factors, FARs and other pertinent regulations and procedures, and the available resources (e.g., fuel, crew endurance).

Assessing: This element is the activity of comparing the current vehicle state (e.g., current lateral position) with the desired state (the current subgoal from planning, e.g., the planned lateral position). This is effectively determining what should be done to obtain the desired state. This includes the determination of the effects of flight-environmental factors, FARs and other pertinent regulations and procedures, and the available resources relative to maintaining the current state or obtaining a corrective state.

Determining actions: This is the activity of determining a corrective state (a transition state) and the actions needed to achieve this

corrective state. This also includes the determination of when the current plan is no longer valid. In this context, it is important to note that the corrective state is the intermediate state required to transition from a current state to a desired state. This corrective state was defined especially for the flight control function because of requirement for continuous, non-discrete actions necessary to support the flight management function. A further description of the corrective state is provided at the end of this section.

Modifying: This element includes the adjusting, changing, or creating of a subplan (or subplans) to accommodate the assessed situation. This is the application of the actions from the "determining actions" element.

Flight control: Flight control (fig. 2) is the second subfunction of the flight management function. The flight control subfunction is the activity of adjusting or maintaining the flight-path, attitude, and speed of the vehicle relative to the flight guidance requirements. The flight control subfunction contains the following elements.

Planning: The flight control planning element is the determination of the control activities necessary to achieve a corrective state. The corrective state for flight control planning is the state required to obtain or maintain the flight-path, attitude, and speed of the vehicle relative to the flight guidance requirements. An example of this element would be the development of a planning subgoal stating that the vehicle needs to increase thrust to obtain 250 kts (where the desired speed of 250 kts originated from flight guidance). This subgoal is a desired state for the other flight control subfunctions.

Monitoring: This element involves the

gathering of all available information about the current control state (e.g., 65% of available thrust is commanded) and the desired control state relative to the flight control planning element. It includes the determination of the effects of flight-environmental factors, aircraft configuration, and other pertinent parameters on maintaining the current control state or on obtaining the corrective control state.

Assessing: This element is the comparison of the current control state with the desired control state. The monitoring element provides input to this element. This element determines if the actual conditions (e.g., 65% of available thrust) match the desired conditions.

Determining actions: This element is the determination of a corrective control state (e.g., the thrust-lever needs to be moved forward) to achieve the desired control state.

Modifying: Modifying is the element of adjusting or changing the control activity to achieve the corrective state.

One unique facet of the flight management function developed in this analysis is the idea of a corrective state. This state was identified for flight management because of the requirement for continuous, non-discrete actions necessary to support the flight management function. That is, the determining actions activity under flight control may continually generate changing, intermediate goals (and states) to satisfy the overall flight control planning goal. To contrast this idea, an activity under systems management (described later) to deal with an abnormal situation would not include the generation of a corrective state as it is defined here. In the systems management activity, the intermediate and end states may be defined a priori from a relatively small set of possible states. Flight control, conversely, deals with a continuum of corrective states to achieve the goal state.

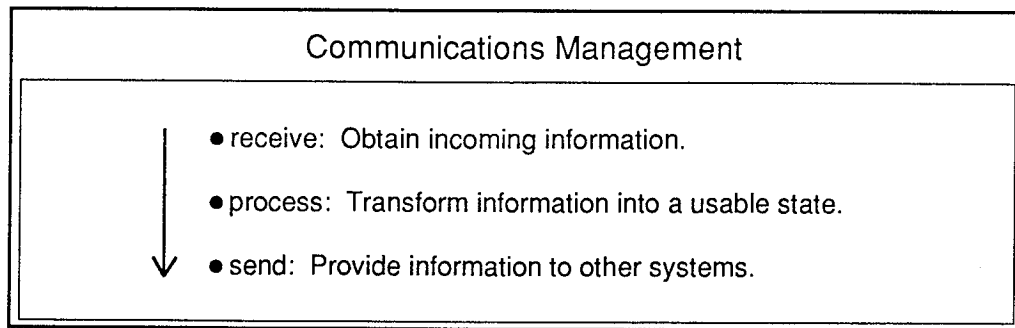


Figure 3. Subfunctions of communications management.

Communications Management

Communication management is the first-level function of managing information flow between information-systems. Examples of information-systems are: each flight deck crew member, flight deck systems, ATC, and the airline company. In addition, information that is not "seen" or used outside a specific information-system is not included in this function. This first-level function was expanded into three subfunctions: receiving, processing, and sending (see fig. 3). An example of the pilot receiving a verbal ATC altitude command will be developed with the definitions.

Receiving: Receiving is the subfunction of obtaining incoming information. It is further divided into three elements.

Monitoring: This element involves the determination of when new information is available. The pilot listens for a message.

Acquiring: This is the activity of actually obtaining the new information. The pilot hears "XYZ123, descend to nine-thousand feet."

Storing: Storing is the element of saving the acquired information in an appropriate (internal) receptacle. The pilot places this message in short-term memory.

Processing: This is the subfunction of identifying and transforming information into a usable state. This function is also divided into

three elements: interpreting, evaluating, and formulating.

Interpreting: This is the element of identifying, classifying, and transforming (where appropriate) the received information. The pilot determines that this is a required altitude change.

Evaluating: This is the element of deciding what to do with the information and where it is to go (determining the user or the destination). The pilot decides that the altitude select knob of the MCP is where this data needs to be sent.

Formulating: This is the element of transforming information into a state suitable for sending to a user or destination. The pilot determines that the MCP altitude knob should be turned down to 10,000.

Sending: Sending is the communications subfunction of providing information to other systems. Information is sent to the appropriate user or destination. The pilot turns the altitude knob to 10,000.

The subfunctions of receiving and sending are the simple ends of the communication management function. The communications processing subfunction, however, embeds many of the traditional management activities. In particular, the elements of evaluating and formulating include the activities of assessing and determining actions (by the determination of the recipient). The overall function of

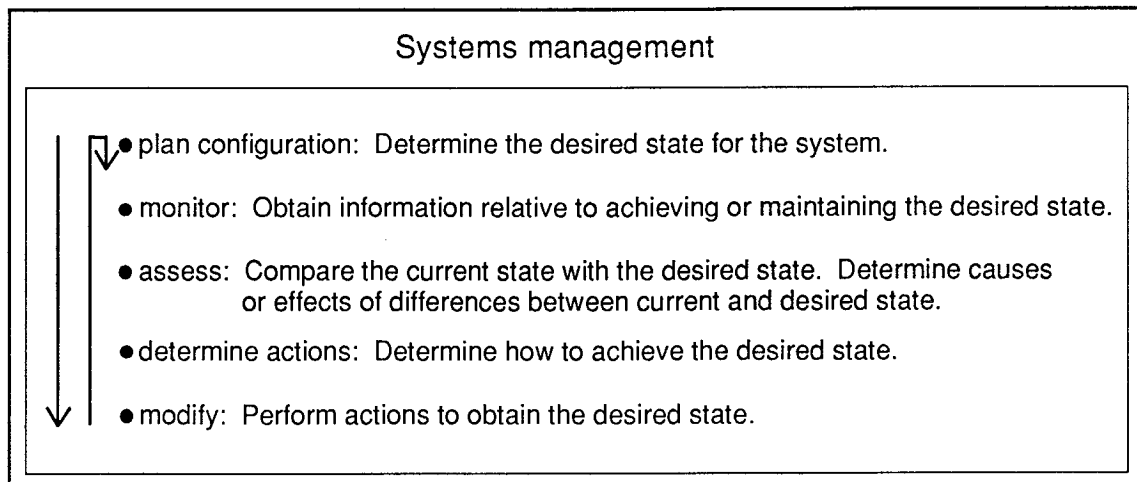


Figure 4. Subfunctions of systems management.

communication management, in the context of this analysis, should be that of an all-inclusive information manager between all information-systems on the flight deck.

Systems Management

Systems management is the first-level function of managing aircraft systems that have operational states or modes that can be externally controlled in a predetermined manner. This function includes the following subfunctions: determining the desired and actual states or modes of a system, comparing and diagnosing differences between desired and actual states or modes, and determining and implementing appropriate actions for obtaining the desired state (see fig. 4). An example of the pilot operating the fuel system will be developed with the definitions.

Configuration planning: Configuration planning is the determination of the desired state for each system relative to the situation. This would include determining appropriate states for systems prior to their use, e.g., the required state for the fuel pumps during an engine fire. Another example of this would be the pilot determining the correct position for the fuel valves prior to starting the engines.

Monitoring: This subfunction involves the gathering of all available information about the current system state and the desired system state. The pilot determines which valves are opened and which valves are closed.

Assessing: For the Systems Management function, the assessing subfunction includes not only comparing the current system state with the desired state, but the diagnosis of the system when these states do not agree. Assessing is divided into the following elements:

Comparing: This element is the comparison of the current state with the desired state. The pilot determines that valve number 3 is closed when it should be open.

Diagnosing: This element involves the determination of the causes or effects of differences between the current state and the desired state. The pilot determines that fuel valve number 3 is closed because the valve-switch is in the off position.

Determining actions: This is the subfunction of determining the actions needed to achieve the desired state. This also includes the determination of when the desired state is no longer achievable. The pilot determines that the

fuel valve switch needs to be in the on position.

Modifying: This is the subfunction of performing the appropriate actions needed to achieve the desired state. The pilot places the fuel valve switch in the on position.

What is both significant and unique about this definition of systems management is that some level of systems management is typically included in all crew-system activities. An example of this would be the pilots use of the flight management system (FMS) to perform a flight routing change. In this example, the pilot would interact with the FMS through the control-display unit (CDU). The FMS would be the agent that was directly conducting flight management. The pilot primarily would be managing the FMS, a systems management function. Therefore, the pilot is indirectly performing flight management and directly performing systems management. This concept of systems management requirements for most crew-systems interactions is a major point that should be considered for flight deck design. By explicitly defining and identifying all crew systems management activities as such, a better understanding of crew physical and cognitive workload may be possible.

Task Management

Task management is the first-level function of managing tasks and associated resources

involved in conducting the mission. This is both a supervisory and a supporting function to the other three major flight deck functions. This function involves monitoring, scheduling, and allocating the tasks and task resources between and for each major function (see fig. 5). In this regard, task resources are agents assigned to perform or aid in the performance of tasks; where an agent could be the pilot, the copilot, or one of various automated systems. This function involves the management of all tasks under Mission Management (tasks within and between the flight management, communications management, and systems management functions).

Task management is a function that has always occurred on the flight deck. In the traditional "aviate, navigate, and communicate," the pilot prioritizes and performs tasks both within and between these functions. To do so, the pilot may start a navigation task, get a voice message from ATC (causing a suspension of the navigation task), and then resume the original task. Task management, then, is the function of managing all of the other tasks. It is composed of three subfunctions: monitoring, scheduling, and allocating.

Monitoring: Monitoring is the subfunction of accumulating all available information about the current state of each task, the desired state of each task, and the overall situation.

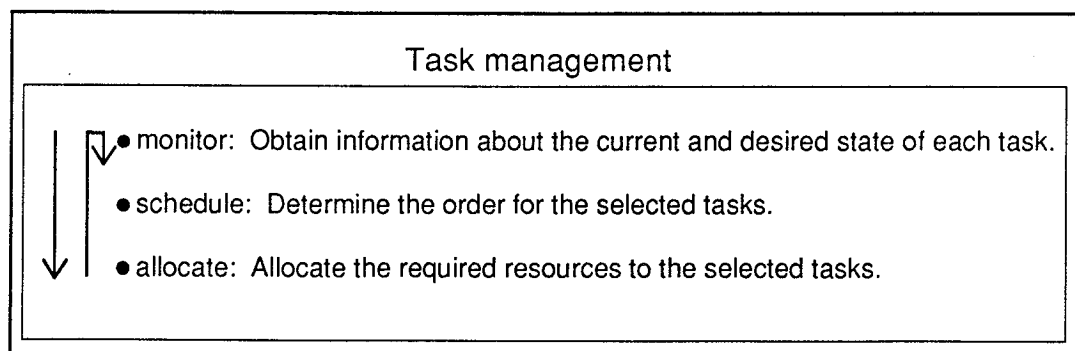


Figure 5. Subfunctions of task management.

Scheduling: This subfunction involves the determination of the overall priority and order in which the selected tasks will be performed. It should be noted that tasks within each major (first-level) function are ordered and prioritized by the generating function. In addition, this scheduling subfunction includes the determination of the available resources and of the resources required. It also includes the determination of when tasks need to be started, interrupted, or resumed.

Allocating: This subfunction involves the allocation of resources to the tasks.

A current technology analogy to this task management function could be the operating system from a multi-tasking computer. In this analogy, the operating system is the executive scheduler for all tasks. It determines the resources available to perform the current tasks and orders the task sequence to best utilize these resources. Additionally, a new, high priority task may cause the operating system to temporarily suspend a lower priority, ongoing task and give the resources allocated to the current task to the new task. Once the new task has been accomplished, the operating allocates the resources back to the original task and restarts the suspended task at the point where it was suspended.

Function Interaction

An important point to consider is that none of these defined, high-level functions would conceptually exist or operate in an independent manner (see fig. 6). Some function interaction would probably be required to accomplish all but the most trivial activity. A current technology example of this interaction is a change of aircraft heading through the pilot's use of the heading control knob on the mode control panel (MCP). Assuming that the aircraft is being (directly) controlled by the autopilot in the heading mode, the pilot would simply turn the heading knob until the desired heading is shown on the

heading-command display. The aircraft would then automatically turn to and maintain the new heading. The pilot would use the heading-command display and the navigation display to monitor the heading of the aircraft. Even with such a seemingly simple task, the pilot is performing the following functions:

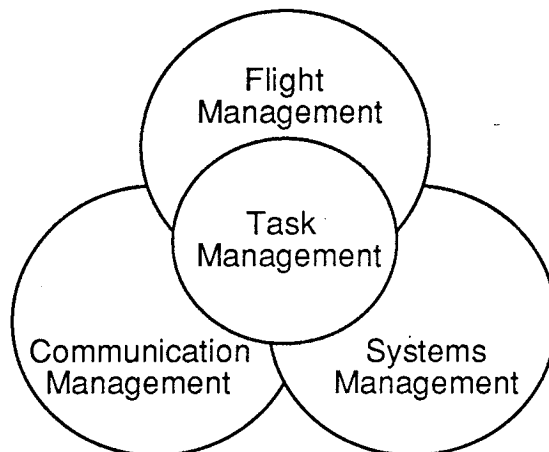


Figure 6. Function interaction.

Flight management: Because the overall intent is to change the flight path of the aircraft, the primary function that is to be accomplished in this example is flight management.

Communication management: Information is being exchanged between the pilot and ATC and between the pilot and the MCP. This is then a case of information flow between information systems and is therefore communications management.

Systems management: The pilot is not directly managing the flight path of the aircraft, but is using the autoflight system to perform this flight management function. Because of this, the pilot is performing a systems management function on the autoflight system.

Task management: If the pilot was performing some other task that was interrupted in order to change the heading, then some task management is being performed.

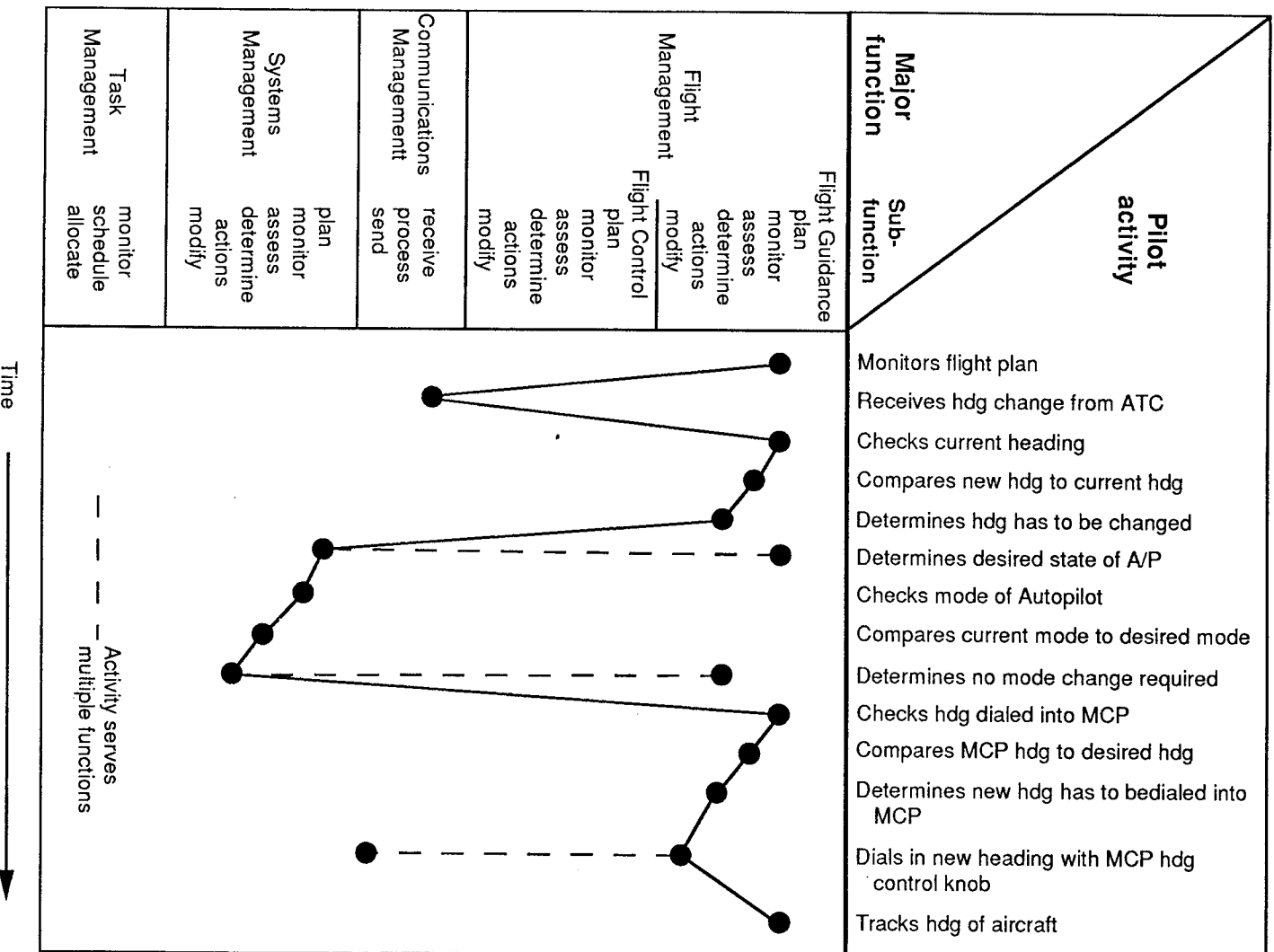


Figure 7. Functional categories and pilot activities mapping.

The mapping of the pilot activities involved in this simple task onto functional categories is shown in figure 7.

From figure 7, it can be seen that a single activity, such as selecting a heading on the MCP, can serve multiple functions. Typically, an activity serving multiple functions will include

interacting with a system that itself is performing or aiding in the performance of another function. This interaction, by definition, includes either communications management or systems management. From this, the point that must be considered is that a design is more efficient and effective if it induces the crew to think about such a multi-functional activity primarily as associated with the underlying, more important function. For example, the activity of the pilot changing a heading on the MCP would be less disruptive (to understanding flight management) if the pilot perceives that this is a modification to the flight plan rather than a communication with the autopilot.

In addition, there are a few points that should be noted about these functional interactions. First, it is assumed that more effort and attention are required to change tasks across functional categories than within a functional category (ref. 7). This is primarily because tasks within functions are more similar than tasks between functions. If the flight deck systems were designed in a manner that requires the pilot to continuously switch between systems management, communication, and flight guidance to obtain a flight guidance goal, then this design would be less efficient than one that allows the pilot to stay primarily within the flight guidance function. That is, it may be a better design that allows the pilot to complete the specific flight guidance task prior to switching to a systems management or a communications management task.

A second point to note is that it is assumed that flight management (flight guidance and flight control) takes priority over systems management, communications management, and task management. That is, the crew should be the most involved in the flight management function. If the crew must devote more time and effort on communications management, systems management, and task management at the expense of flight management, then the design is probably ill-conceived.

Concluding Remarks

One of the initial steps in an integrated flight deck process is to define the primary flight deck functions needed to support the mission goals of the vehicle. This would allow the design team to evaluate candidate concepts in relation to their effectiveness in meeting the functional requirements. It could also provide a better understanding and allocation of activities in the design, an understanding of the impact of a specific system on overall system performance, and an awareness of the total crew performance requirements for the design. This paper describes one candidate set of functional categories that could be used to guide an advanced flight deck design. Four functions were identified and are defined as follows:

Flight management: the function of managing all parameters relative to flight planning, flight guidance, and flight control.

Communications management: the function of managing information flow between information-systems. This function includes both internal and external communications. It includes, but is not limited to, the flight deck crew.

Systems management: the function of managing aircraft systems that have operational states or modes that can be externally controlled in a predetermined manner.

Task management: the function of managing tasks and associated resources involved in conducting the mission.

These functions encompass all of the activities required to support the mission goals of a commercial transport aircraft. By taking a global perspective in defining the flight deck functions and using these functions in developing the design, a better understanding of the total design requirements and the implication of design decisions on the final design product may be obtained.

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